The Kata-thermometer as a Measure of Ventilation.

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In two papers previously published, one by Leonard Hill, O. W. Griffiths and M. Flack,* and the other by Leonard Hill and D. Hargood-Ash,† the kata-thermometer was described in detail, and formulæ were given connecting the heat loss with temperature, wind velocity and vapour pressure. Various discrepancies were found to occur, however, and seeing that the kata-thermometer has become recognised as a measure of ventilation the whole matter has now been carefully reinvestigated. Large wind tunnels such as those at the National Physical Laboratory, which were not available during the war, owing to the urgency of aeroplane work, were now at our disposal.

Experimental Work.

To obtain known wind velocities for the experimetal work two methods were adopted, that of the "wind tunnel" where the air is drawn through a long tunnel by means of a propeller at one end, and that of the "whirling arm" where the "kata" is made to move through the air on a revolving arm. The wind tunnel work was carried out in the engineering department at the National Physical Laboratory by kind permission of Dr. T. E. Stanton, where Miss D. Marshall gave us valuable assistance in the determination of wind velocities; also at East London College, where Dr. N. A. V. Piercy was good enough to allow us the use of the tunnel and to help us in determining the wind velocities.

Observations with the whirling arm method were taken at the Physiological Laboratory, Oxford, and at the National Institute for Medical Research, Hampstead. The observations at Oxford were made: (i) in a large room, all the doors and windows of which were closed, and air currents were further reduced by surrounding three sides of the table on which the apparatus stood by screens covered with several thicknesses of brown paper. The fourth side had to be left open, so as to admit of light, and of a point from which to view the "kata." Air draught from below was prevented by means of horizontal screens placed on the table supporting the apparatus. A moving air current of known velocity was obtained by clamping the "kata" to a brass rod fixed at one end to the central pillar of a Sherrington recording drum, and revolving it in a horizontal circle; (ii) other observations were made in the respiration chamber, which is a closed room of $10 \cdot 5 \times 6 \cdot 5 \times 4 \cdot 5$ ft. capacity. The experiments by the whirling arm method at Hampstead were very similar to those carried out at Oxford. A screen of American cloth, 4 ft. high, was erected on the floor of a large room, so as to form an enclosure 4 ft. square, the top being open. The door and windows of the room were closed, so that the air inside the enclosure was still. A transparent celluloid window was inserted all round the screen at the height of the "kata" stem, so that readings might be taken of the cooling, and the thermometer read.

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* 'Phil. Trans.,' B, vol. 207, pp. 183–220 (1916).

† 'Roy. Soc. Proc.,' B, vol. 90, pp. 438–447 (1919).

In the whirling arm method the actual velocity, v, of the "kata" is given by

$$v = \frac{2\pi rn}{t},$$

where r is the radial distance of the "kata" from the axis of revolution, n the number of revolutions in the time t (estimated by stop-watch). L. V. King* and others have shown, however, that this is not the true velocity relative to the air, a certain "swirl" being set up by the revolution of the arm. This was determined and allowed for in our observations. The procedure by which this swirl was allowed for will be described later.

The Dry "Kata"—Wind Velocity and Temperature.

As shown in the previous papers, sources of radiant heat being absent, the rate at which the "kata" cools in air depends almost entirely upon the wind velocity and air temperature. It is shown that the heat loss per second per square centimetre of bulb surface is obtained by dividing a "factor," determined for each instrument by the time of cooling, expressed in seconds, which the alcohol meniscus takes to fall from 100° to 95° F., the unit of heat being a millicalorie (1000 millicalories = 1 grm. calorie). This is known as the "cooling power," H, and it was found that a connection between the variables is given by an expression of the form

$$H = (a + b\sqrt{v})\,\theta$$

where v is the wind velocity and θ the difference between the mean temperature of the range of cooling, viz., 36·5° C. (97·7° F.), and the air temperature in degrees Centigrade, whilst a and b are numerical constants.

To obtain the constants a and b, a number of observations of the cooling power were taken, the temperature and wind velocity being accurately determined at the same time. The results are shown graphically in figs. 1 and 2.

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* L. V. King, 'Phil. Trans.,' A, vol. 214, p. 373 (1914).

Each point in these graphs is the mean value obtained from three to seven observations of cooling, taken consecutively. Where points coincide the observations were taken at different times. Several kata-thermometers were used, the factors in each case being verified. The high velocity observations were taken in the wind tunnels and the low velocity ones by the whirling arm method. Unfortunately, owing to experimental difficulties, it was not found possible to make these two methods overlap, the lowest wind tunnel velocity available being 3·05 metres per second, and the highest whirling arm velocity for the dry "kata" 1·77 metres per second.

No equation of the above form will apply for all velocities over the range tested, but from the value $\sqrt{v} = 1$ to $\sqrt{v} = 4{\cdot}2$, that is, between the velocities 1 metre per second and 17 metres per second, a curve may be drawn to fit the points as shown, the equation of which is

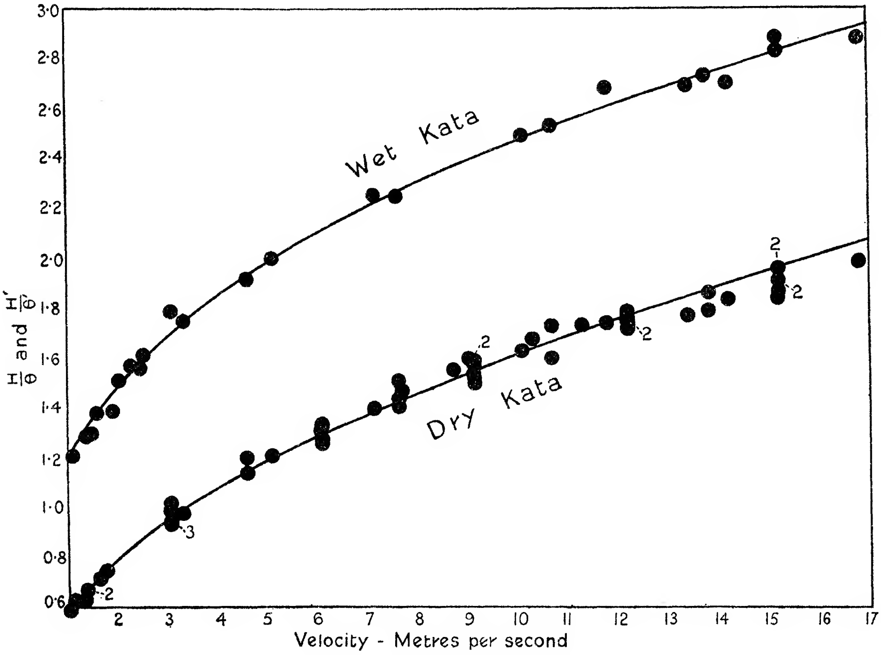

FIG. 1.

$$H = (0{\cdot}13 + 0{\cdot}47\sqrt{v}) \,.\, \theta. \qquad \text{(i)}$$

It should be noted that the above limits include observations in air currents obtained by both methods. Below 1 metre per second velocity another curve may be drawn, of which the equation is

$$H = (0{\cdot}20 + 0{\cdot}40\sqrt{v}) \,.\, \theta. \qquad \text{(ii)}$$

These two lines are shown with the experimental points as the lower curves in the diagrams.

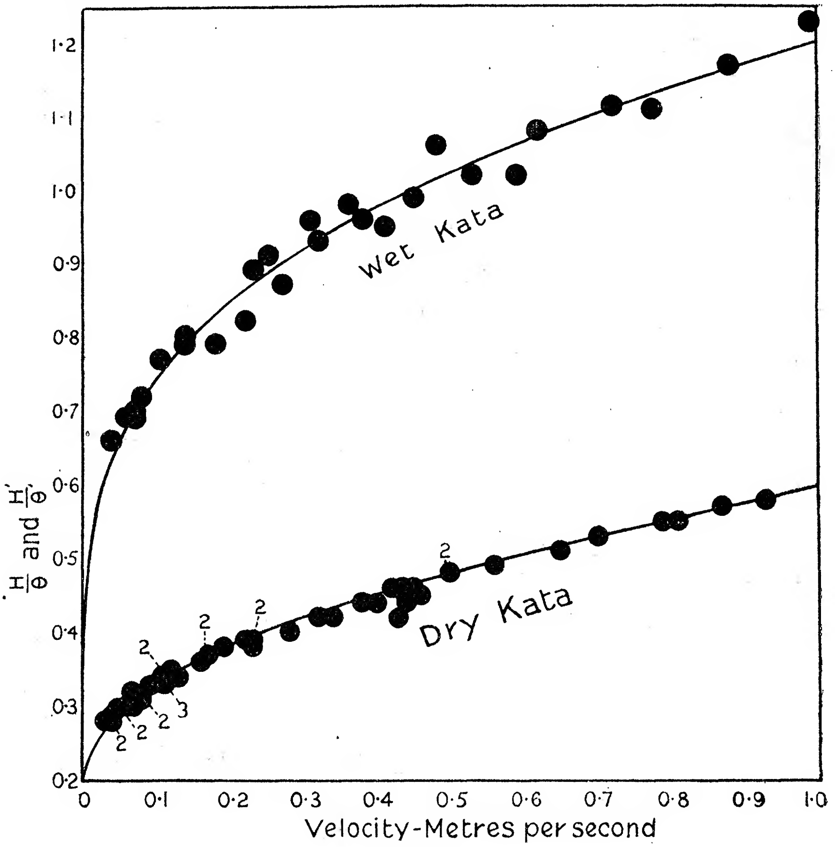

FIG. 2.

The Wet "Kata"—Wind Velocity, Temperature, and Evaporation.

Wet "kata" observations were made in a similar manner to the dry "kata" ones, except that the bulb of the instrument was covered with a muslin "finger," which remained moist during the time of cooling. In this case a velocity as high as 2·50 metres per second was obtained by the whirling arm method. With the wet "kata" heat is lost by the evaporation which takes place in addition to the heat lost by convection and radiation, as in the dry "kata," so that the wet cooling power, H′, is always greater than the dry cooling power, H. It is evident, then, that in addition to the temperature and wind velocities, some term must be introduced to take account of the humidity of the air. In the 'Phil. Trans.' paper the formula deduced from theory and experiment was of the form

$$H' = (a+b\sqrt{v})\,\theta+(c+d\sqrt{v})\,(F-f)^{4/3},$$

where H′ was the heat lost per second per square centimetre from the wet "kata," v the wind velocity, F the maximum vapour pressure at 36·5° C., f the actual vapour pressure of the air at the time of the observation, θ equal to the difference between 36·5° C. and the air temperature, and a, b, c, and d numerical constants. This was afterwards modified to the form

$$H' = (a' + b' \sqrt{v})\,\theta + (c' + d'\,v^{0\cdot 3})\,(F - f)^{4/3},$$

which was given in the later paper.

Our new investigations give an equation of the form

$$H' = (a'' + b'' \sqrt{v})\,\theta + (c'' + d'' \sqrt[3]{v})\,(F - f)^{4/3},$$

but, just as for the dry "kata," two equations are found to be necessary, one for velocities greater than 1 metre per second and one for velocities less than this. These equations are

$$H' = (0\cdot 13 + 0\cdot 47 \sqrt{v})\,\theta + (0\cdot 035 + 0\cdot 098 \sqrt[3]{v})\,(F - f)^{4/3} \qquad \text{(iii)}$$

for velocities greater than one metre per second, and

$$H' = (0\cdot 20 + 0\cdot 40 \sqrt{v})\,\theta + (0\cdot 060 + 0\cdot 073 \sqrt[3]{v})\,(F - f)^{4/3} \qquad \text{(iv)}$$

for velocities less than 1 metre per second.

In each case the first term on the right-hand side of the equation represents the dry "kata" heat loss.

These expressions are cumbersome for practical use, so that when the question was re-investigated we proposed to try if a formula in which the humidity was represented by the wet bulb temperature would give satisfactory results; that is to say, a formula of the form

$$H' = (a + b\,v^x)\,\theta',$$

where θ' is the difference between 36·5° C. (97·7° F.) and the *wet* bulb temperature, t', a and b being numerical constants, and x some power to which the velocity, v, had to be raised.

When our experimental values of H'/θ' were plotted against the wind velocity values, as shown in the upper curves of figs. 1 and 2, it appeared that such a relation existed between the variables, and that, considering the whole range of velocities from zero up to 17 metres per second, the value $x = 1/3$ gave satisfactory results.

We may, therefore, write an empirical wet "kata" formula in the form

$$H' = (a + b \sqrt[3]{v})\,\theta',$$

where H′ is the heat loss per second per square centimetre, v the wind velocity, and θ' the difference between 36·5° C. (97·7° F.) and the wet bulb temperature, t'. As before, two equations are necessary to cover the whole range. The constants a and b, when v is in metres per second, H′ in millicalories per second, and θ' in degrees Centigrade, are given by the following two equations:—

$$H' = (0{\cdot}10+1{\cdot}10\sqrt[3]{v})\,\theta' \text{ for velocities greater than 1 metre per second,} \quad \text{(iii}a\text{)}$$

$$H' = (0{\cdot}35+0{\cdot}85\sqrt[3]{v})\,\theta' \text{ for velocities less than 1 metre per second.} \quad \text{(iv}a\text{)}$$

Our results with the wet "kata" in winds are only over a limited range of humidities (the wet bulb temperature varying from 9·5° to 19·8° C.), owing to the difficulty of controlling the humidity in the large rooms in which the wind tunnels are situated. In the case of still air, however, it is possible to obtain more varied conditions, and considering the still air wet "kata" formula

$$H' = 0{\cdot}27\,\theta+0{\cdot}085\,(F-f)^{4/3}, \qquad \text{(v)}$$

given in the original paper, it seems probable that for very dry or very moist air, equations (iii) and (iv) are more correct than (iii*a*) and (iv*a*). It is not possible to find an equation for still air of the form

$$H' = a\theta'.$$

This can be seen at once by putting in fixed values of the wet bulb temperature in (v) and varying the humidity. In this way it is found that a varies from 0·5 to 0·7 as the temperature and humidity vary from 10° C. and 10 per cent. relative humidity to 20° C. and 100 per cent. relative humidity. For any given wet bulb temperature the value of a increases with the humidity, the increase being much more rapid at low relative humidities.

With respect to the wind velocity index, when considering evaporation, we find that observers have come to many different conclusions on the matter. John Dalton gives the value as unity. A number of late investigators found it to be 0·5.[*] Recent observations made by Bigelow,[†] in which he determined the rate of evaporation of water from pans 2 to 6 ft. in diameter in wind of various known velocities, gave results agreeing with Dalton's. It may be pointed out that for certain ranges of wind velocity, *e.g.*, between the velocities of 0·3 and 2·5 metres per second, our results hold for a value of 1 for this index, but many more than two equations would be necessary to cover the whole range of our experimental work with this value, while for the index of 1/3 very close agreement is obtained by the use of two equations of the same form. The velocities recorded by Bigelow were mainly low. It can hardly be expected that the conditions of evaporation from large vessels and from such instruments as the "kata," where the evaporation surface is vertical and the water only a thin film, should be identical.

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[*] *Cf.* Hann, 'Lehrbuch der Meteorologie,' Ed. 3, 1915.

[†] Bigelow, 'Monthly Weather Review,' 1910, p. 307.

It will be noticed that the rate of cooling, both of the dry "kata" and the wet "kata," begins to take an abnormal course at the same point, viz., an air velocity of 1 metre per second. There can be little doubt that the abnormalities are due to convection currents. Currents of warm air, heated by the cooling "kata," tend to rise vertically from the sides of the bulb, and this air considerably impedes the rate of cooling of the "kata" in still air. It can have little or no effect in the presence of horizontal air currents of fair velocity, as it will be swept aside, but air currents of low velocity are not sufficiently powerful to effect this completely, and in consequence the rate of cooling is retarded.

Determination of Swirl.

It has already been mentioned that in the whirling arm experiments account must be taken of the swirl produced; that is to say, the true velocity of the "kata" relative to the air is less than the actual velocity, because the air is carried round with the revolving arm to a certain extent. A method similar to that described by L. V. King* was adopted to determine the amount of swirl. In the case of the Oxford experiments, a "kata" was fixed at one end of a horizontal arm and it was revolved at the rate of 1, 2, or 3 metres per second, and its bulb passed close to the bulb of another "kata," which was fixed in a stationary position. Cooling observations of the stationary "kata" were made while the moving one revolved at room temperature. When the centres of the bulbs were 2 cm. apart there was only 2 mm. space between the bulbs.

From the series of data obtained we were able to calculate what the H/θ values would have been had it been physically possible for the bulb of the stationary "kata" to occupy the place through which the bulb of the moving "kata" passed in its revolutions. From them it has been possible to calculate the velocity of swirl of air against the stationary "kata" bulb by using an approximate formula already determined from observations taken without allowance being made for swirl. These swirl velocities vary from 6·5 to 7·96 per cent. of the velocity of the revolving "kata," but they are all subject to a certain deduction. Now the velocity of swirl found by King when using a wire was 6 per cent.; therefore, assuming that this value holds likewise with the "kata"—the assumption being warranted by the above experimental results—then it follows that the values must be reduced by 6 per cent. This correction has been applied to all the Oxford results.

Similar experiments at Hampstead gave a value for the swirl of about 9 per cent., which was deducted from the calculated velocities before recording.

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* L. V. King, 'Phil. Trans.,' A, vol. 214, p. 373 (1914).

The Kata-thermometer in Practical Use as an Anemometer.

To test the accuracy of the wind formulæ for practical purposes, series of experiments have been carried out at Kew Observatory, where observations were taken by kind permission of Dr. Chree; at High Beech, Loughton; at Walberswick, by Mr. P. F. Alexander; and at Eskdalemuir, by Mr. P. N. Shelton, under the direction of Mr. L. F. Richardson. The results are shown in the Table. It will be seen that in all cases the wind as determined by the "kata" agrees well with that given by other anemometers.

Place of observation.	H.	$\theta = (36 \cdot 5 - t)$.	Velocity "kata."	Cup anemometer.	Kew anemometer.	Eskdalemuir air meter.	Time of observation.
							mins.
Kew	24·2	17·5	7·1	6·4	6·0	—	8
	21·5	18·0	5·1	5·7	6·0	—	3
	21·9	18·0	5·4 } 5·8	5·5 } 5·7	6·3 } 5·9	—	5
	22·9	17·9	6·0	5·5	4·9	—	7
	21·9	17·9	5·6	5·7	6·0	—	7
High Beech	25·1	22·0	4·7	4·9	—	—	5
	27·0	22·0	5·5	5·7	—	—	10
	25·5	22·2	4·7 } 5·4	5·5 } 5·6	—	—	10
	27·3	21·5	5·9	5·4	—	—	6
	28·6	22·0	6·2	6·5	—	—	6
Walberswick	35·5	33·2	4·0	4·0			
	35·5	33·2	4·0	4·4			
	48·0	37·3	6·1	5·3			
	33·1	37·6	2·5	2·8			
	45·1	37·5	5·2	5·0			
	55·5	37·6	8·3	7·5			
	40·4	37·1	4·2	4·6			
	32·5	34·6	3·0	3·0			
	29·0	28·2	3·7	4·1			
	32·0	30·4	3·8	4·2			
	29·4	29·6	3·3	3·5			
Eskdalemuir	23·2	33·6	1·3	—	—	2·1	
	34·6	33·8	3·6	—	—	2·9	
	27·7	33·1	2·2	—	—	2·4	
	24·2	33·1	1·6	—	—	1·7	
	22·5	30·3	1·7	—	—	0·7	
	40·1	35·8	4·4	—	—	4·7	
	26·8	32·8	2·2	—	—	2·3	
	35·8	29·5	5·3	—	—	5·2	
	31·5	33·2	3·0	—	—	2·5	
	26·7	32·7	2·2	—	—	2·2	
	36·8	30·6	5·2	—	—	3·5	
	28·0	31·6	2·6	—	—	2·4	

Summary.

From the above considerations then we consider that we are justified in saying that the "kata" is an instrument which shows a definite relation between the heat loss and the surrounding conditions, and that this relation may be expressed in the form

$$H = (a + b\sqrt{v})\,\theta$$

for the dry "kata," where H is the heat loss per second per square centimetre of "kata" bulb surface, θ being the difference between 36·5° C. and the dry-bulb temperature, and v the wind velocity in metres per second. The equation takes the following numerical forms for air velocities above and below 1 metre per second:

$$H = (0{\cdot}13 + 0{\cdot}47\sqrt{v})\,\theta \quad \text{(ii)} \qquad \text{and} \qquad H = (0{\cdot}20 + 0{\cdot}40\sqrt{v})\,\theta. \quad \text{(iii)}$$

The wet "kata" formulæ are more complex (see p. 201), but for ordinary atmospheric temperatures and humidities an approximation is yielded by the formula

$$H' = (a' + b'\sqrt[3]{v})\,\theta',$$

where H' is the heat loss per second per square centimetre of wet "kata" bulb surface, and θ' is the difference between 36·5° C. and the wet bulb temperature.

This equation takes the following numerical forms for air velocities above and below 1 metre per second,

$$H' = (0{\cdot}10 + 1{\cdot}10\sqrt[3]{v})\,\theta' \quad \text{(iv)} \qquad \text{and} \qquad H' = (0{\cdot}35 + 0{\cdot}85\sqrt[3]{v})\,\theta'. \quad \text{(v)}$$

(It should be noted that the above equations are not true when v is less than 0·04 metre.) By means of equations (ii) and (iii) the "kata" may be used as an anemometer, both for estimating wind velocities out of doors, or the velocity of air currents indoors for purposes of ventilation. For the latter purpose it has a special value, for it estimates cooling effects of air currents whether unidirectional or eddying.